EEMS0017

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

Impact of CAV Technologies on Travel Demand and Energy

Joshua Auld, Mahmoud Javanmardi, Ehsan Islam, Dominik Karbowski, Tom Stephens, Aymeric Rousseau – ARGONNE NATIONAL LABORATORY

2017 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review – June 7, 2017

Argonne NATIONAL LABORATORY | INL Idaho National Laboratory | BERKELEY LAB | OAK RIDGE National Laboratory | NREL NATIONAL RENEWABLE ENERGY LABORATORY

Project Overview

SMART CAV Task 1.3: Impact of Connected and Automated Vehicles (CAVs) on Energy, GHG and Mobility in Metropolitan areas

Timeline	Barriers
• Project start date : Oct. 2016 • Project End date : Sep. 2019 • Percent complete : 10%	• Computational models, design and simulation methodologies • Lack of data on individual behaviors relating to CAV • Integration of disparate model frameworks • High uncertainty in technology deployment, functionality and impact

Budget	Partners
• FY17-FY19 Funding: $1,920,000 • FY17 Funding Received : $635,000	• Argonne (Lead) • ORNL, LBNL • Texas A&M • University of Illinois at Chicago

Project Relevance

Challenge

- High-level penetration of level 4 CAVs will impact travel:
  – Reduced congestion due to platooning… if VMT stay the same
  – Potentially higher VMT because driver can repurpose driving time
  – Past analyses have not evaluated combined effect of these two forces
- High uncertainty of energy impact

Objectives

Quantify the regional energy impact of CAV deployment:

- **Considering interrelated factors**:
  - Congestion relief/increase through roadway capacity changes
  - Value of travel time (VOTT), and potential change in VMT
  - Market penetration and fleet distribution
  - Household activity patterns
- **Using disaggregate integrated transportation systems model (POLARIS)**

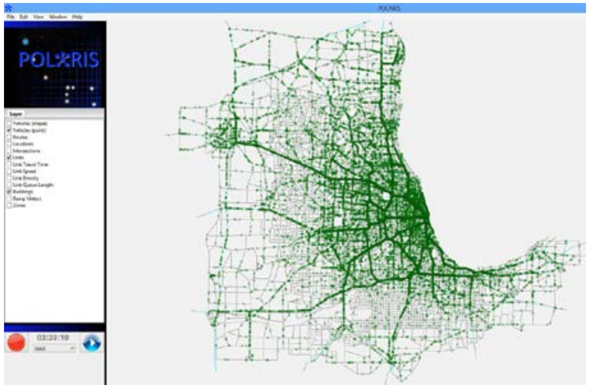
- Bridge the research gaps between:
  - Quantitative analysis of vehicle technology and transport policy energy impacts
  - Structure for approaching complex interactions, multi-dimensional analysis
  - Incorporating the many dimensions of individual decision-making behavior

APPROACH

Approach

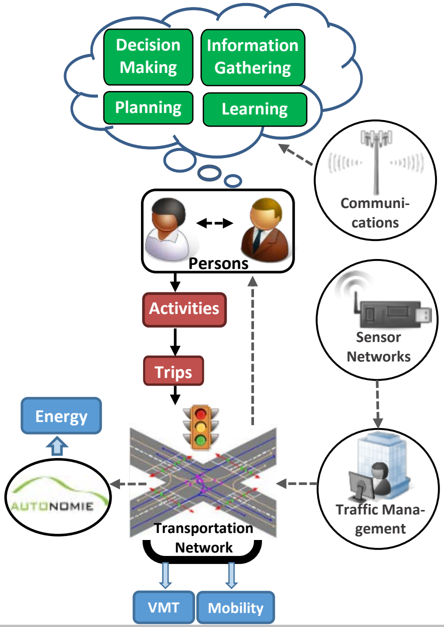
- **Update tools** used for transportation and energy simulation, POLARIS and Autonomie, to support the analysis
  - Add individual-level CAV vehicle technology choice framework
  - Update traffic flow modeling to account for CAV
  - Update Value of Travel Time (VOTT)
- Develop a **case study** and analyze energy outcomes:
  - Evaluate impact across a range of costs for privately-owned vehicles equipped with level 4 automation
  - Combine with analysis of feasible reductions in the VOTT savings associated with the availability of automated driving
  - Evaluate energy impact when combined with various powertrain technology scenarios
- Test the methodological approach on **large-scale, real-world networks**, e.g. Chicago metropolitan area model (10 million travelers)
- Case study to serve as preliminary assessment as more detailed information and models come in from SMART mobility and other programs

POLARIS Is Uniquely Designed to Study Complex Transportation System Questions

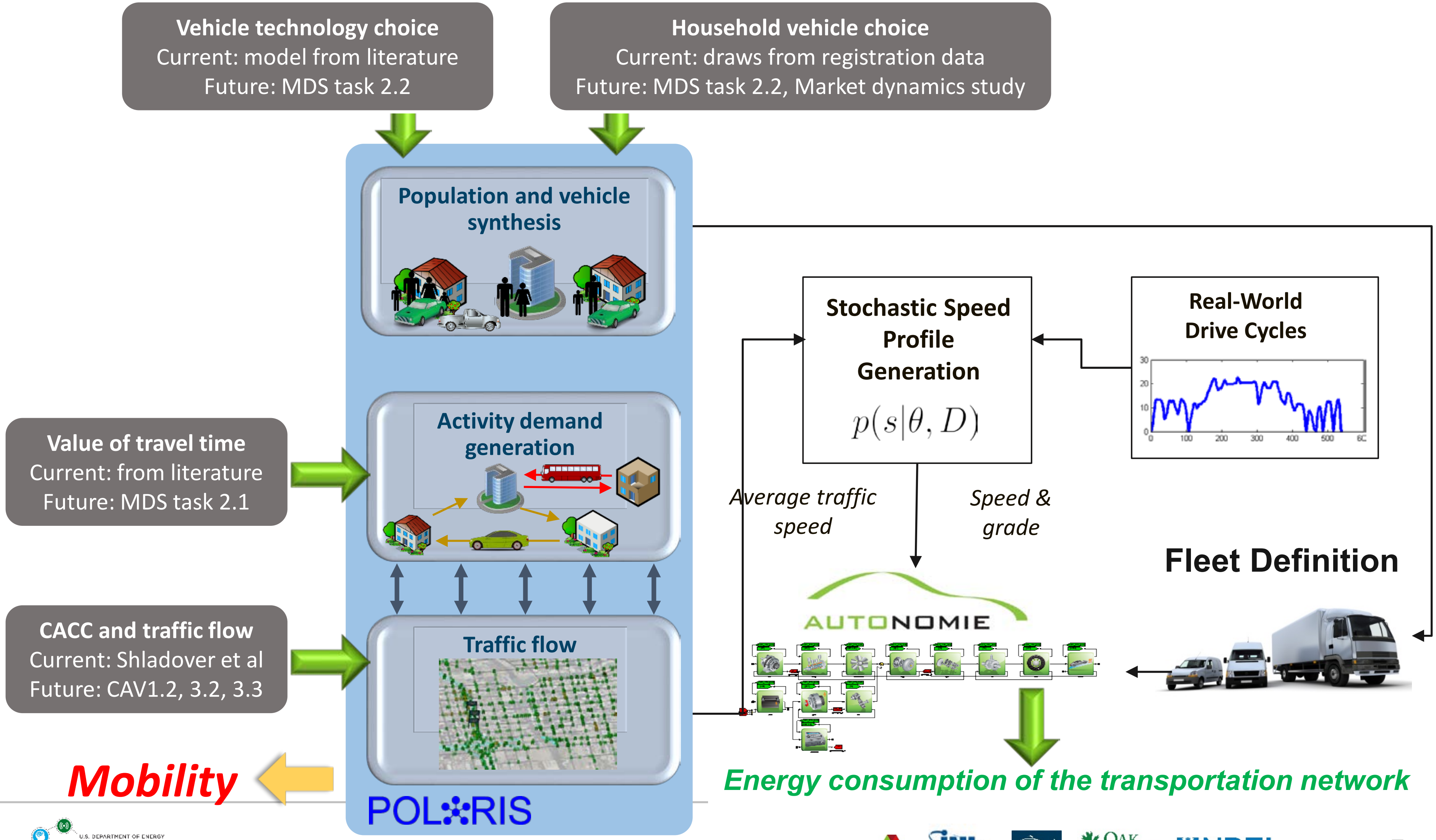


- POLARIS designed to run large-scale studies:
  - Written in C++, multi-threading
  - Chicago model ≈ 10M travelers ≈ 30M trips (per day) ≈ 3h simulation time (vs several days for other tools)
- POLARIS is open-source, with a dedicated team of developers and transportation experts at Argonne

- POLARIS is designed from the ground-up to accommodate new modes and transportation technologies and evaluate the energy-impact:
  - ***Agent-based****: each traveler is modeled individually, has specific behavior and adjust behavior to transportation supply*
  - ***Activity-based****: travel demand is derived from modeled activities (work, school, leisure, etc.)*
  - ***Integrated****:* ***demand*** *(e.g. origin/destination) and* ***supply*** *(routing, traffic flow) are* ***integrated*** *in the same platform, allowing direct interactions (e.g. replanning/rerouting in case of unusual travel time)*
  - ***Energy****: POLARIS + Autonomie outputs energy consumption in the context of evolving vehicle powertrain technologies*



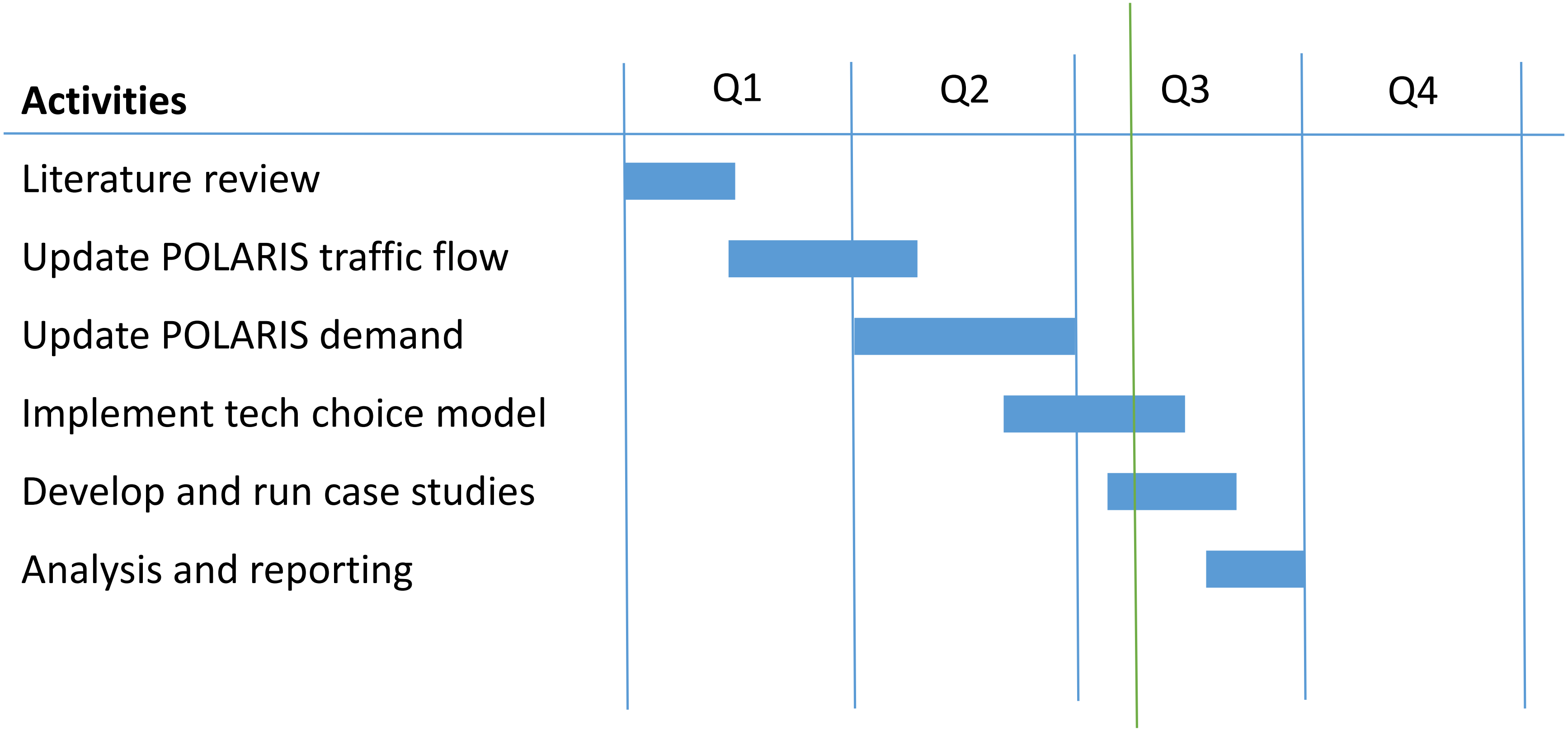
Estimating Regional Energy use with POLARIS + Autonomie



U.S. DEPARTMENT OF ENERGY SMARTMOBILITY

Argonne NATIONAL LABORATORY · INL · BERKELEY LAB · OAK RIDGE National Laboratory · NREL

Milestones


Activities
Q1
Q2
Q3
Q4
Literature review
Update POLARIS traffic flow
Update POLARIS demand
Implement tech choice model
Develop and run case studies
Analysis and reporting

TECHNICAL ACCOMPLISHMENTS

Modeling Changes in Traveler Value of Travel Time (VOTT) Due to CAVs

- Literature review:
  – To our knowledge, no study formally predicts VOTT change (or time cost or VOTT savings) in CAVs
  – More focus on performance improvements due to CAVs
  – Still unknown what business models will emerge as CAVs develop, and how people's activities, travel choices, and attitudes will change as a result (Fagnant and Kockelman, 2014, 2015; Mahmassani, 2016)
- Most studies reviewed here suggest that:
  – VOTT in a CAV would be less than the VOTT of a driver in a passenger car,
  – Closer to the VOTT of a seated transit passenger in an uncrowded vehicle (Litman, 2009; Schrank et al., 2012; Bierstedt et al., 2014; Gucwa, 2014)
- **Select 50% to 70% of auto driver time-cost as feasible range**

Study	VOTT in CAV or of a non-driving passenger in a car
Litman, 2009	35% to 70% of the wage rate
Schrank et al., 2012	$16 per hour
Bierstedt et al., 2014	25% to 50% of the wage rate
Gucwa, 2014	50% of the VOTT of the driver to VOTT in high-speed rail

Category	LOS A-C	LOS D	LOS E	LOS F	Waiting		
					Good	Average	Poor
Commercial vehicle driver	120%	137%	154%	170%		170%	
Comm. vehicle passenger	120%	132%	144%	155%		155%	
City bus driver	156%	156%	156%	156%		156%	
Personal vehicle driver	50%	67%	84%	100%		100%	
Adult car passenger	35%	47%	58%	70%		70%	
Adult transit passenger – seated	35%	47%	58%	70%	35%	50%	125%
Adult transit passenger – standing	50%	67%	83%	100%	50%	70%	175%
Child (<16 years) – seated	25%	33%	42%	50%	25%	50%	125%
Child (<16 years) – standing	35%	46%	60%	66%	50%	70%	175%
Pedestrians and cyclists	50%	67%	84%	100%	50%	100%	200%
Transit Transfer Premium					5-min.	10-min.	15-min.

This summarizes recommended travel time values, based on Waters (1992) with adjustments to reflect the quality of transit passenger waiting, walking and transfer conditions. These default values should be calibrated and adjusted to reflect specific conditions and the preferences of affected groups.

Source: Litman (2009)

Modeling Consumer Adoption of Automation Technologies: Willingness-to-Pay (WTP)

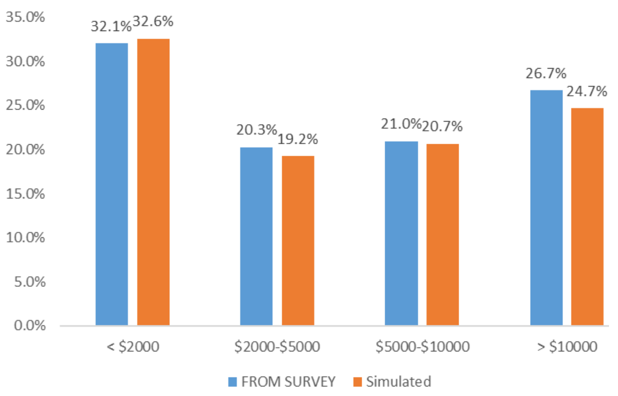
- Need model to distribute technology geographically for < 100% penetration cases
- Literature review:
  – Several models developed for automation adoption based on stated preference surveys
  – All generally develop some ordered choice model for WTP levels
  – Include demographics, cost, and elicited attitudes toward tech. and CAV
- Implemented Bansal et. al. model for evaluation:
  – Implemented in Polaris
  – Calibrated for Chicago so that WTP distribution is same for Austin

	Bansal et al. (2016) University of Texas Austin	Daziano et al. (2016) Cornell	Shabanpour et al. (2017) University of Illinois at Chicago
Survey	347 Austinites (2014)	1,260 individuals, Nationwide (2014)	1,253 respondents in Chicago (2016)
Automation Level	3 and 4	Partial (automated crash avoidance), Full	3 and 4
Average WTP	Level 3: $3,300 Level 4: $7,253	Partial automation : $3,500 Full automation: $4,900	Level 3: $3,225 Level 4: $5,475
Modeling Technique	bivariate ordered probit model	logit-based model with discrete continuous heterogeneity distributions	Random thresholds hierarchical ordered probit
Variables Used	Socio-Demographic, Landuse, VMT, Familiarity with automation technology, Driving history (past crashes)	Socio-Demographic, Region, Familiarity with automation technology, Fuel cost, Purchase price	Socio-Demographic, Landuse, Individual/personal specific (congestion, safety, cost and comfort sensitivity, etc.)

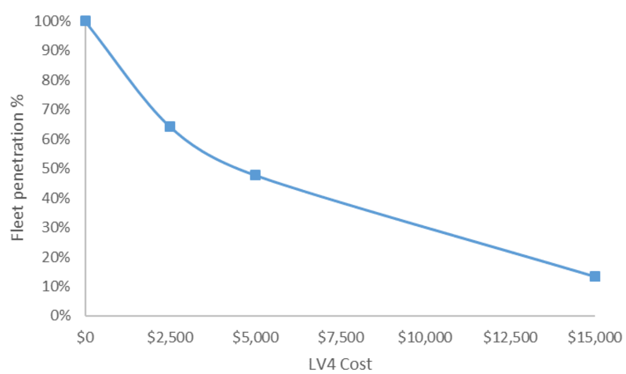
Implemented Willingness-To-Pay (WTP) Model for CAV Adoption and Tour Level Vehicle Selection Model

- Implemented and calibrated the Bansal et al. model
  - Use to assign CAV technology to household vehicles at various costs
  - Not designed as a replacement for detailed market penetration work:
    - Simple method to distribute technology for preliminary studies
    - Many assumption, i.e. **all who are willing to pay for CAV do so**
    - No diffusion through fleet, **no market dynamics**, etc.
  - Gives reasonable geographic distribution of CAV technology when coupled with household vehicle choice model
- Vehicle selection model controls scheduling and assigns specific vehicle for each tour
- **Travelers with CAV have reduced travel time cost (50% or 70% of baseline cost) for auto mode**

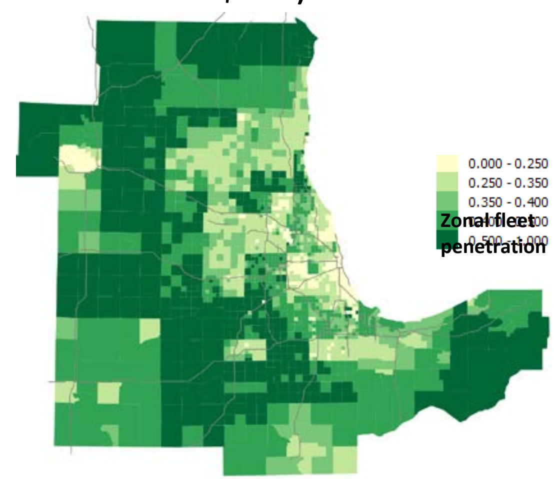
Fitted Level 4 WTP distribution



Level 4 fleet penetration at cost



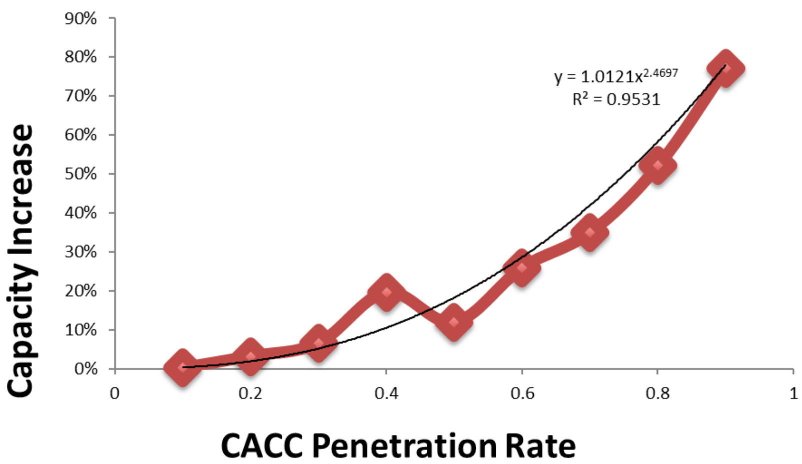
Level 4 geographic distribution (cost = $5000)



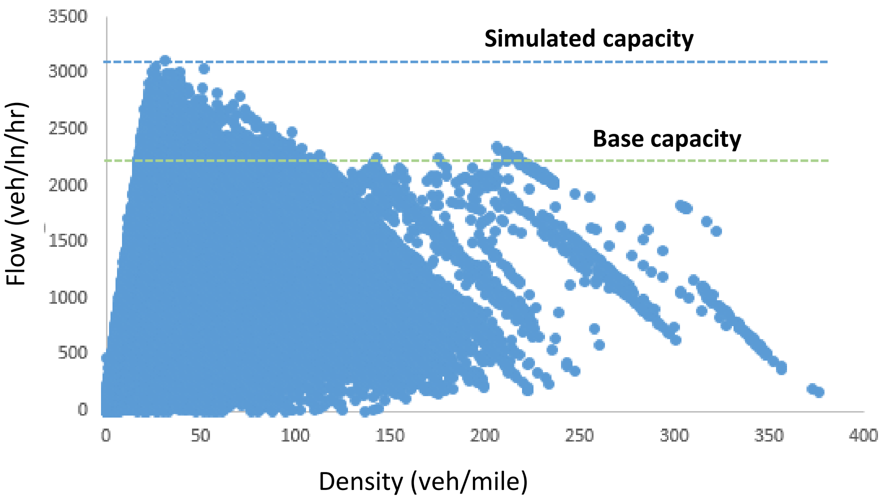
CACC Traffic Flow Model Implemented in POLARIS Network Simulator

- Cooperative Adaptive Cruise Control (CACC) allows for reduced vehicle headways and reduced impact of driving behavior
- Simulation and field studies show link capacity increases with increasing CACC penetration
- Simulate regional effects using dynamic link capacities:
  – Number of CACC vehicles in each link continuously updated ⇒ disaggregate penetration rate
  – Capacity adjusted every simulated minute according to fitted equation in figure below
- Simulated ~41% capacity increase at 75% penetration seen on highway links at the network level, as expected

Link capacity increase vs. CACC penetration



Network fundamental flow diagram for highway links: 75% penetration

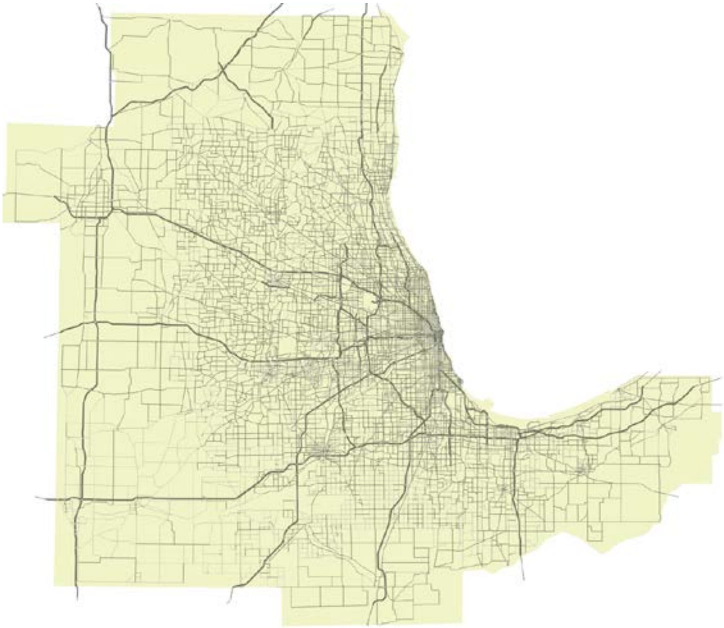


U.S. DEPARTMENT OF ENERGY SMARTMOBILITY Systems and Modeling for Accelerated Research in Transportation

Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · BERKELEY LAB · OAK RIDGE National Laboratory · NREL NATIONAL RENEWABLE ENERGY LABORATORY

CAV Deployment Scenarios: Setup and Results

- Develop three sets of scenarios runs: 0) Base, 1) -30% VOTT, 2) -50% VOTT,
- Vary by 4 levels of CAV cost for non-base scenarios
- Evaluate for Chicago-area based using previously developed POLARIS model
  - 10.2 million travelers
  - 27.9 million automobile trips
  - 31,278 links in 1,944 zones for the 20 county region



Case study setup

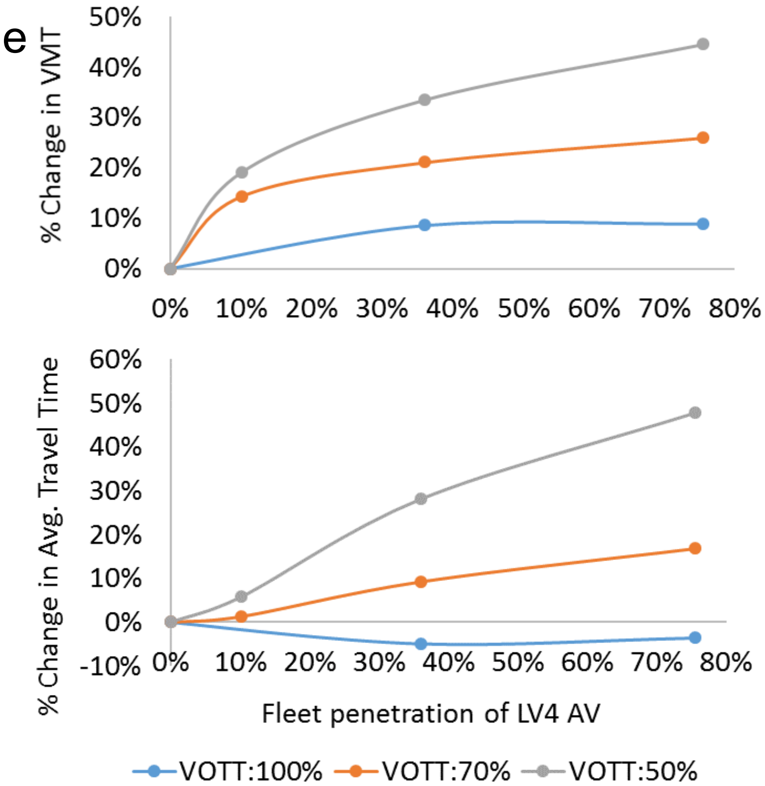
Run	AV cost	VOTT change	Fleet pen.
0	--	0%	0%
0.2	$5,000	0%	47.8%
0.3	$0	0%	100.0%
1.1	$15,000	-30%	13.4%
1.2	$5,000	-30%	47.8%
1.3	$0	-30%	100.0%
2.1	$15,000	-50%	13.4%
2.2	$5,000	-50%	47.8%
2.3	$0	-50%	100.0%

Impact of CAV Technologies on Mobility

- Travelers with access to CAV technology take longer trips
  - 11.8 mi baseline average trip length increases to over 17.4 mi at high penetrations
  - Longer trips as VOTT reduction is increased ⇒ reduced burden of driving
  - Some congestion increase – travel time increase 7% faster than travel distance
- Some of VMT increase mitigated by improved system performance ⇒ ~5% reduction in travel time due to capacity improvement

Run	AV** pen.	VOTT reduction	VMT (millions)	VHT (millions)	Avg. travel time (min)	Avg trip length (mi)
0	0	0%	268.0	8.17	23.4	11.79
0.2	36.1%	0%	291.2	7.86	22.2	12.50
0.3	75.5%	0%	292.0	7.96	22.5	12.73
1.1	10.1%	30%	306.5	8.37	23.7	13.38
1.2	36.1%	30%	324.6	9.04	25.5	14.21
1.3	75.5%	30%	337.7	9.64	27.3	14.82
2.1	10.1%	50%	319.2	8.74	24.7	13.99
2.2	36.1%	50%	357.8	10.45	29.9	15.77
2.3	75.5%	50%	387.4	11.92	34.5	17.40

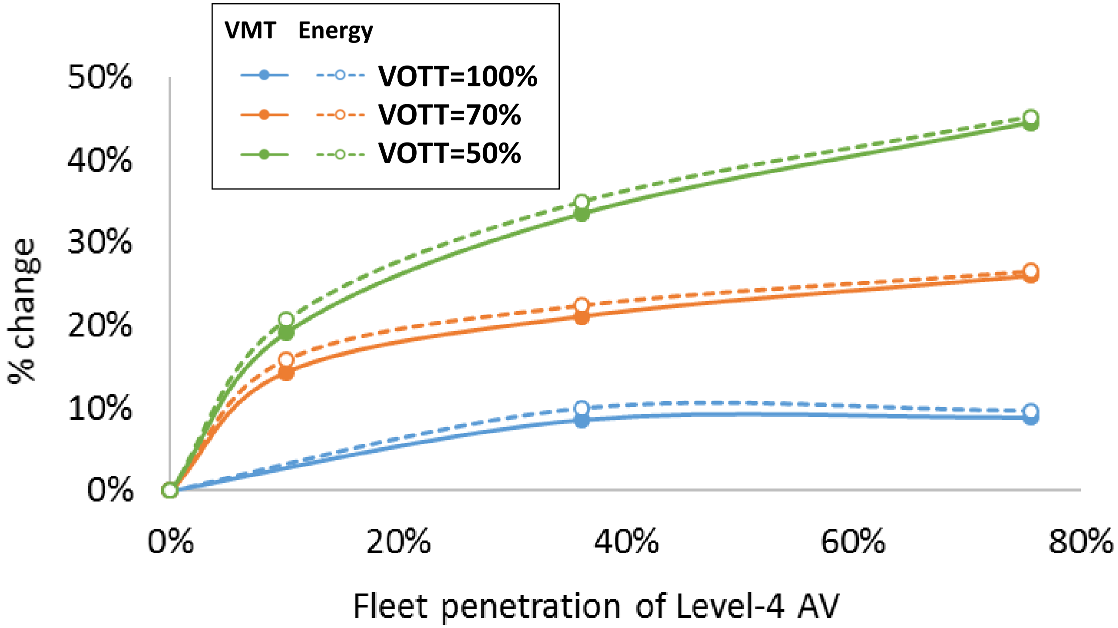
** including non-local and truck traffic



Impact of CAV Technologies on Regional Energy Use

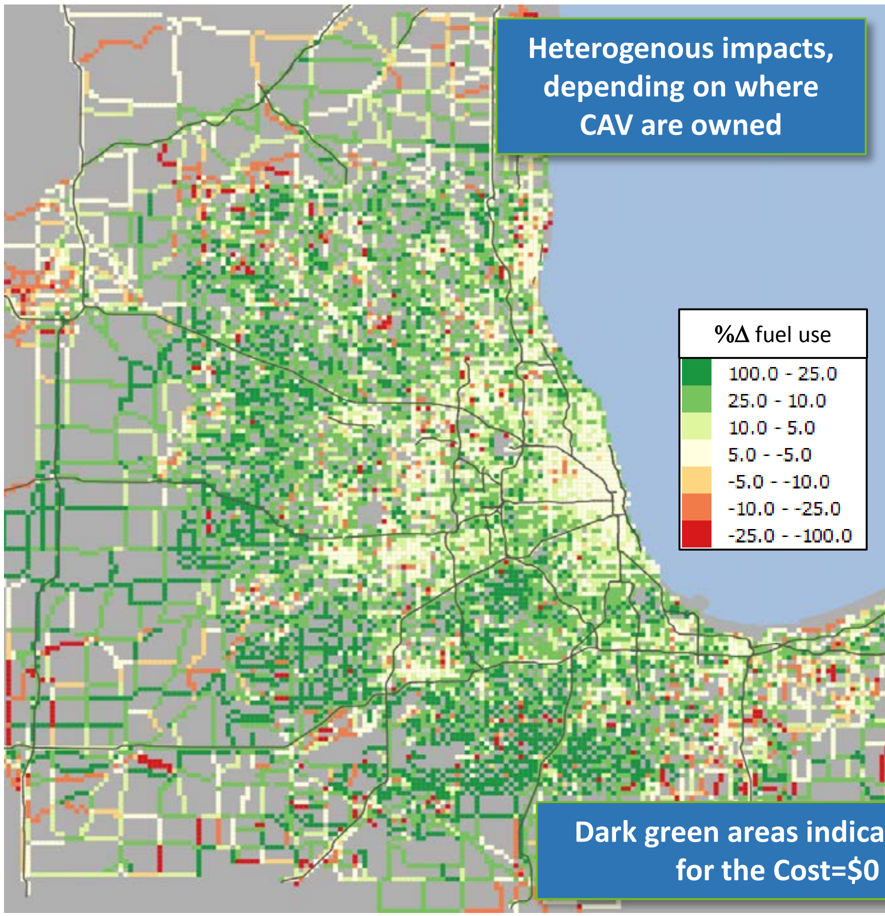
- Autonomie process using synthesized vehicle type distributions and 2040 vehicle technology
- Substantial increase in fuel use as CAV penetration increases, at a decreasing rate
- Fuel consumption increased 43% in worst case scenario although efficiency up slightly
- Larger reduction of VOTT increases fuel use due to longer trips

Run	AV pen.*	VOTT change	Fuel consumption (MM gallons)
0	0%	0%	4.85
0.2	36.1%	0%	5.34
0.4	75.5%	0%	5.32
1.1	10.1%	-30%	5.62
1.2	36.1%	-30%	5.94
1.4	75.5%	-30%	6.14
2.1	10.1%	-50%	5.85
2.2	36.1%	-50%	6.55
2.4	75.5%	-50%	7.05



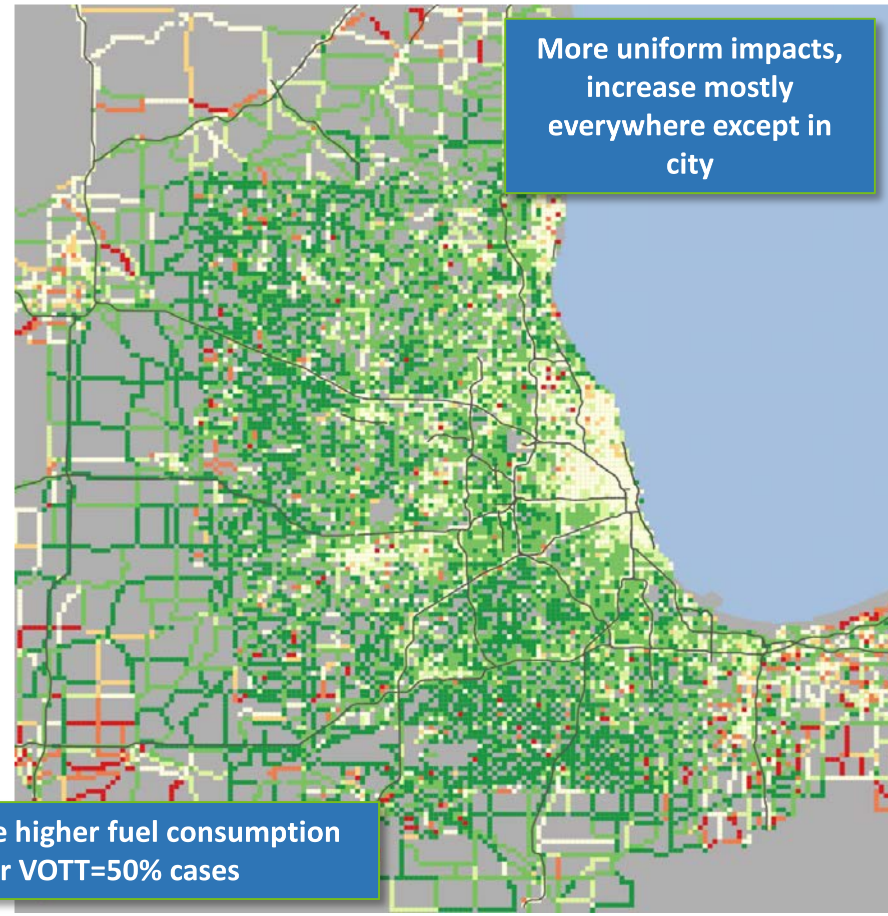
Geographic Distribution of Fuel Use Changes

Difference in fuel use between cost \$0 vs cost \$15000 (VOTT = 70%)



Heterogenous impacts, depending on where CAV are owned

Difference in fuel use: VOTT 50% vs VOTT 70% (Cost = \$0)



More uniform impacts, increase mostly everywhere except in city

Dark green areas indicate higher fuel consumption for the Cost=\$0 or VOTT=50% cases

Response to Previous Year Reviewers' Comments

Project was not reviewed in the past

Partnerships and Collaborations

TEXAS A&M UNIVERSITY	Improvement of CAV traffic flow model using CAV-specific fundamental diagrams (future work)
THE UNIVERSITY OF ILLINOIS AT CHICAGO	Activity scheduling, resource allocation and time of day modeling
UNSW SYDNEY	Value of time and time use literature review Future work: time use analysis and scheduling behavior
OAK RIDGE National Laboratory	Integration with MA3T, providing vehicle market forecasts
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Vehicle registration data for base year models

Remaining Challenges and Barriers

- **Behavior modeling**:
  - Modeling current traveler behaviors is complex and requires **large amounts of data** for validation
  - Forecasting behavior changes due to **non-existent technologies** is even more difficult
- **Vehicle choice model** used for study models geographical distribution, but many simplifying assumptions were used
- **Traffic flow model** needs to be dynamically adjusted for each of the road segments capacity given the current position of vehicles – allow for formulating platoons based on link entry times, and expand technologies beyond CACC
- Current analysis focuses on **privately-owned CAVs** but does not include CAV-enabled travel modes (e.g. automated taxis)

Proposed Future Research

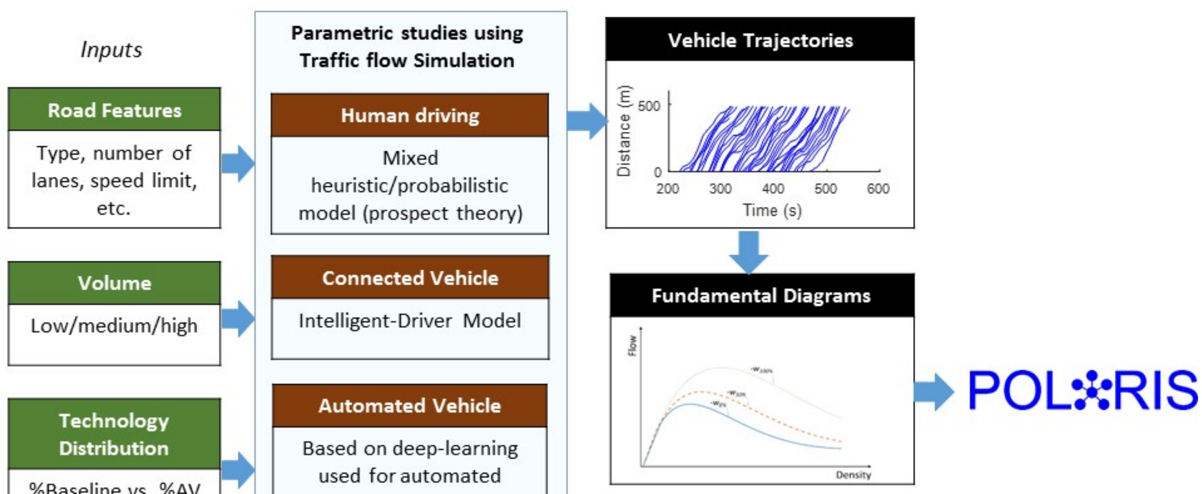
- Integrate **data** and models from surveys about travelers attitudes towards CAVs (e.g. WholeTraveler)
- Develop a **vehicle choice model** that relates socio-demographic characteristics to the likelihood of owning a vehicle with CAV; integrate with MA3T market penetration model
- Improve **traffic flow model** to better model platooning and CAV driving:
  - allow the capacities to be dynamically adjusted for each of the road segments capacity given the current position of CAV vehicles on that specific link
  - allow for platoon formation based on link entry times, instead of utilizing average penetration rate and capacity update function
- Account for **Zero-Occupancy-Vehicles**: self-driving vehicles serving multiple members of the household
- Extend analysis to include **non-privately owned CAVs**, including ridesharing, carsharing, autonomous fleets, etc.
- **Transfer** results from regional level to national level

Any proposed future work is subject to change based on funding levels

Proposed Future Research

Improving the Traffic Flow Module to Dynamically Model Changes in Capacity Due to CAVs

- New traffic flow model will rely on “multi-variate” fundamental diagrams in POLARIS, which will **dynamically** adjust to the number of CAVs present on each link
- Fundamental diagrams will be generated using a traffic flow micro-simulator developed at Texas A&M University
- Microsimulation is a higher-fidelity model, but does not scale up well.



Any proposed future work is subject to change based on funding levels

Summary

- **Relevance**:
  - Combined analysis of CAV energy impacts across multiple dimensions simultaneously, including traveler behavior, network operations, and vehicle technologies for assessment of VTO technology programs
- **Key achievements**:
  - Powerful energy estimation tool for regional analysis allows us to analyze the intersection between transport policy and vehicle technology
  - Case study demonstrates energy impacts for privately owned level-4 automated vehicles over a feasible range of cost, willingness to pay and travel time valuations
  - Results: **between 21% and 43% increase in fuel use** for an assumed VOTT range of 70% to 50% of baseline auto VOTT
- **Next steps**
  - Connect to vehicle choice models for realistic fleet distribution
  - Incorporate research into time use behavior and travel time valuations
  - Improve traffic flow model
  - Expand analysis to additional CAV technologies and shared use cases
  - Evaluate transferability for national level energy evaluations